DESIGN MODELS AND MODEL BASED DESIGN IN FLUID FLOW WITH APPLICATION TO MICRO AIR VEHICLES
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Abstract: Our focus has been on structural enablers for very low order design models and for model-based flow control, including the flow physics underpinnings of low order flow models. Basic theory investigations concentrated primarily on Galerkin models: We derived from the NSE the essential role and form of mean field models and developed a novel none-equilibrium statistical closure and implied sub-grid turbulence models. Mean-field models now predict lift dynamics and high frequency actuation. With harmonically-pure mode-sets, mode interpolation maintains minimum model order across changing operating conditions, and is assisted by a new, efficient POD computation. Experimental studies were done in conjunction with a related MURI project, and complemented independently supported, long-term international team collaborations. We explored new feedback paradigms, including implementing duty ratio feedback modulation of pulsating jets, validated by MAV lift enhancement, and Lagrangian models in feedback for drag reduction behind a 3D bluff body. The research is presented in 7 published / accepted journal papers, 2 under review and 1 in preparation, 2 Book chapters, 17 refereed conference papers and 14 conference abstracts, the material in a forthcoming book, as well as several colloquia presentations and a dedicated short course on flow modeling and control.

1. Enablers for Low Order Galerkin Models (LOGMs) for Control Design

1.1 *A basic theory of Galerkin mean field models.* Mean field models incorporate low dimensional representations of the bilateral interactions of fast flow-field fluctuations with a slowly varying base flow [2],[J:4,6,9],[BC1],[C:6,16],[P:1,5,7,10,14]. These interactions are fundamental to the transition of flow configuration from linear instability of the steady flow to the marginal stability of attractors' energy levels. In [2] we introduced the *shift mode* as a compact encapsulation of mean flow variations, governed by a Galerkin counterpart of the Reynolds equation. Analyzing the reduced order system, [2] demonstrated that the resulting Landau-type Galerkin system is dynamically essential for the dynamic representation of transients. Initial validation, in [2], used the laminar cylinder wake as a simple benchmark. Subsequent studies revealed counterpart structures in the separated flow over airfoils [J:1,4-6],[BC1],[C:2,5,6,16],[P:1-4,7-10,14]. One research thrust aimed to solidify mean-field theory through a detailed analytic and quantitative investigation of its NSE-foundations [J:6,9][C6][P-4,5,7,14]. This investigation had 3 components: Direct analysis of the band-pass filtered NSE reveals both necessity of a mean-field model, including the nonlinear coupling of stability properties of the fluctuation with mean field variations, and the ideal structure of the shift mode. Second, we introduced a novel concept of quantitative transient energy flow rate

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analysis, and used that analysis to demonstrate the dominant role mean filed variations play in determining fluctuation growth and decay rates. Thirdly, we have demonstrated that ideal, analytic and practical, computationally efficient definitions of the shift mode are essentially equivalent, thus validating the use of the empirical shift mode introduced in [2]. Related studies include modeling-enablers for high frequency boundary actuation, dynamic lift, and transient flow conditions. Viable subgrid models, compensating for truncated energy are discus, are discussed in §2.

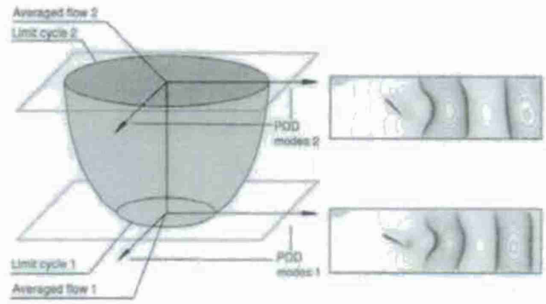

FIGURE 5. Invariant manifold for transition between two operating conditions: $\alpha = 30°$ and $\alpha = 45°$

Figure 1. The manifold formed by the dominant POD mode pair of the separated flow over an airfoil at a varying AOA. The vertical direction represents changes in both the mean field and the AOA

1.3 *Mean field theory: high-frequency actuation models.* The attenuating effect of open loop high frequency actuation on instabilities at unrelated frequencies is a fundamental flow control mechanism. Despite its significance, this mechanism has so eluded an analytical representation in reduced order Galerkin models, and has been resolved only by ad-hoc terms. In [J6],[P7,9] we proposed a *physically based* least order mean-field model capable to do just that. The model comprises 2 mode pairs for the dominant natural and actuated frequencies, and 2 mean field, shift modes represented mean field corrections driven by the respective Reynolds stress contributions of the fluctuating mode-pairs. The model explains the attenuating affect as mediated by actuated changes in the mean field: The Reynolds stress formed by the actuation leads to changes in the mean field. Stability properties of fluctuations are varied with changes in the mean field. In particular, the linear instability at the natural oscillation frequency disappears, in what amounts to an actuated subcritical Hopf bifurcation.

1.4 *Mean field theory: dynamic lift models.* With few extensions [1] standard lift models are confined to quasi-steady state representations or to conceptually equivalnt harmonic balancing representations (e.g., for Helicopter blades). A by-product of [J6] is a first systematic framework for dynamic lift modeling. As an illustration, our objective is to resolve the response of the lift to fast MAV maneuvers, wind gusts, and actuation. A simple link of aerodynamic forces to the LOGM is obtained by substituting the Galerkin approximations of *both* the velocity and the pressure into the first principles expression

$$c_l = \frac{1}{0.5\rho U_\infty^2 c}\left(-\int_\Gamma p\mathbf{n}\,dS + \nu\int_\Gamma \nabla\mathbf{u}:\mathbf{n}\,dS\right)\cdot\mathbf{e}_y.$$

In this framework the lift is dynamically tied to changes in the dominant coherent flow structures. This work continues to date through our MURI collaborations and experimental refinement and validation of the proposed framework [C:1,3,11,13,15,17].

1.5 Mode deformation, mode interpolation and minimal mode sets for long transients. Traditionally, LOGMs use modes obtained from a single operating condition, such as the POD mode of an attractor. The very purpose of flow control is to significantly alter and deform the coherent structures that dominate the flow e.g. due to flow reattachment of over an airfoil. As has been broadly recognized, these changes necessitate resolving controlled changes in dominant coherent structures. The use of richer mode-sets and realtime adaptation are common features of solutions proposed by the flow control community. Both these features increase realtime complexity. Additionally, the fact that, at any given time the number of dominant coherent structures remains small, and that richer mode-sets account for moderate deformations in these structures, may also entail a raise in the numerical sensitivity of dynamic observers, that now need to discern between relatively similar modes. Instead we suggest *state dependent mode deformations* over low dimensional manifolds: The time coefficients of the Galerkin expansion remain the LOGM states, but now they multiply modes that vary with the operating condition. For example, in a minimal order model of the separated flow over an airfoil, the first two modes are identified (up to state-space rotation) with the dominant unstable Eigenmodes, near the steady solution, and with the dominant POD mode-pair, near the natural attractor. Means to explicitly parameterize modes are based on simple interpolation algorithms, and the explicit derivation of the modes is required in only few operating conditions. We applied this approach to a pitching and actuated airfoil and to the cylinder wake in [J:5,10], [BC1], [C:2,8].

1.7 Harmonically specific modes. The paradigm of parameterized / interpolated mode-sets is feasible when important modal properties remain invariant under mode deformation. Key among these properties, in very low order models, is the link of modes to harmonics of the dominant temporal frequencies, even as these frequencies gradually change along transients between operating points. Standard POD modes often blend multiple spatial and temporal frequencies. To derive *harmonically-linked modes*, we use a dynamic estimation of the instantaneous frequency and an FIR filter bank to partition data trajectories into single frequency components [C:5,10],[P:3,4]. POD analysis is applied separately to each frequency component to obtain the desired modes. A preliminary high resolution POD compression of the original data is suggested, to dramatically reduce computations entailed by temporal filtering. Parameterization of mode deformation is a direct by-product. The procedure was first tested for an actuated NACA0012 airfoil [C5] and later applied to transient simulations of 2D and 3D pitching flat plates [C10]. Under independent support it was also applied, with remarkable success, to derive local mean field models for the dynamics near bifurcation branches in an analysis of the vortex breakdown phenomenon. The latter example is particularly

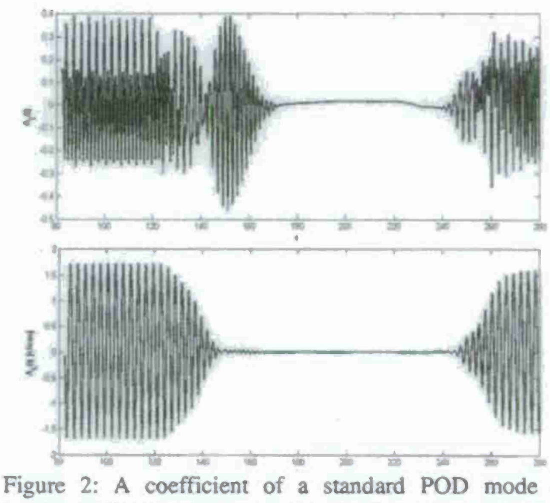

Figure 2: A coefficient of a standard POD mode is harmonically rich (top), compared with a harmonically-specific mode (bottom), both for a pitching flat plate.

challenging both because of the co-existence of multiple fixed points and local basins of attractions and to the strong effect of a short pipe on oscillatory dynamics.

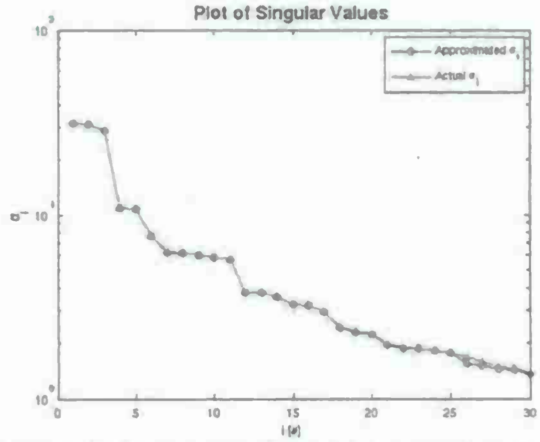

Figure 3. POD and approximate POD eigenvalues for a long transient of a pitching airfoil are nearly identical.

1.8 Balanced POD system identification for periodic orbits. One key deficiency of POD modes is directly tied to their main advantage, i.e., their easy computation from empirical data. Neither the optimality criterion nor the actual computational procedure weigh the dynamic significance of selected modes. Indeed, strikingly, POD analysis is invariant under temporal re-sequencing of the snapshots used. In contrast, *balanced truncation* is a method driven precisely by the underlying (linear) dynamics. Our MURI colleague C. W. Rowley adapted this method to fluid flow systems. A persistent shortcoming of this method is its focus on linear dynamics, and originally, a single fixed point. We joined the Princeton team in an extension to periodic orbits, as an enabler to effective modeling of periodically dominant transients and attractors [J8].

1.9 An accelerated *POD computation.* Even the computations necessary to extract POD modes can become taxing for high dimensional data consisting of long / rich transients. We propose an accelerated algorithm based on data partitioning in space and/or time: Following POD analysis of each partition, it is replaced by far smaller set whose first and second statistical moments approximate those of the original set. POD analysis of the reassembled global set is then guaranteed to approximate the exact POD of the original dataset. Computational savings are nearly linear (over a predicted range) in the number of partitions, and like the standard POD, a sought resolution is guaranteed. The method give rise to multiple space-time partitions and provides a formal justification for efficient iterative shortcuts. Results, validating the advantages of the procedure were presented in [C:5,9],[P:3,4] Links with concepts of sparse samplings are the subject of current investigation.

2. Turbulence Statistical Closure and Sub-grid models

Subgrid turbulence models are required to compensate for neglected length and time scales, and for the effects of truncated energy cascades. Prevalent practice is to calibrate eddy viscosities as added dissipation in the linear term of an LOGM. While successful in many cases, failures abound, suggesting a need for a new approach. The thermodynamic statistical closure problem is a daunting challenge in turbulence physics. In addition to the basic science value of a solution, related to the LOGM framework, a successful turbulence model is essential to overcome the aforementioned roadblock.

2.1 A new theory of *finite-time thermodynamics (FTT) for Galerkin systems*. Cutting through a persistent Gordian knot, this novel framework treats single or aggregate modal energies as thermodynamic degrees of freedom. A balance of external interactions (i.e., production and dissipation) with rates of triadic, lossless energy transfer between modes, governs state dynamics. Simple closure formulae are derived from a postulated set of first principles, based on observed properties and dimensional analysis. Central axioms include the statistical independence of unrelated modes and the exsistence of an energy cascade from energy-rich to energy-poor modes. The dynamical system correctly predicts the energy cascade and redistribution in a number of benchmark tests, ranging from Burger's equation to the homogeneous shear turbulence. The FTT framework was reported in [J:2],[C:7,14],[P:6,11].

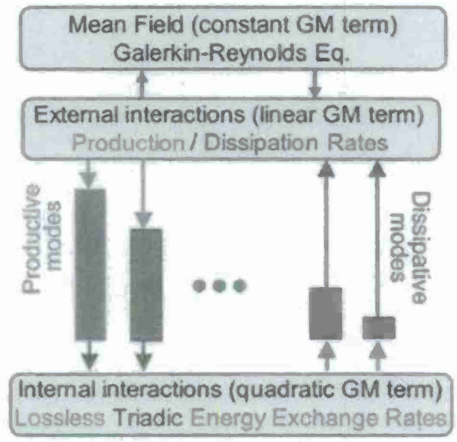

Figure 4. Energy flow rates determine modal energy balancing in the FTT model.

2.2 *A unified framework of generalized Landau models.* The structure of the FTT model reveals the intrinsic nonlinearity of energy exchanges between resolved Galerkin modes, mean-field modes and unresolved turbulence. A new class of hybrid models, based on this observation, aims to resolve the entire range of length and time scales: Mean field models resolve the largest scales and slowest time variations, an FTT based turbulence model resolves small scales statistics with pseudo-modes that captures the time variations of the aggregate energy at these scales, and standard LOGM terms resolve the usually targeted dynamics of dominant coherent structures. In particular, the implied turbulence model structure reveals both plausible reasons for eddy viscosities entailed difficulties, and alternative formalisms for simple sub-grid models. Outlines of the new framework are delineated in [J7],[P14] and work on further development and refinement continues to date.

3. Experimental Benchmarking & Verification

The design of robust feedback mechanisms utilizing few noisy sensors, is key to a realistic close control methodology. We used two benchmarks to validate our developments. One is the experimental drag reduction of the flow over a 3D bluff body (Fig. 5) at the Berlin Institute of Technology. The other is the semicircular, low aspect-ratio wing plan, developed as part of the MURI project. The primary support for the latter is under the main MURI grant and results are reported accordingly, although, for completeness, we list here publications related to both.

3.1 *Feedback design utilizing a reduced order vortex models (ROVMs).* This work relates to our joint work with for both rapid prototyping and implementation. Wake attenuation is achieved by symmetrizing the two shear layers, using a single pressure gauge: Pulsed blowing at the upper leap is synchronized at a preferred phase difference with the sensed pressure at the lower leap. A 40% pressure deficit reduction is achieved. This robust mechanism easily adapts to changing flow conditions where open-loop actuation at the two leaps becomes ineffective, while requiring only 60% of the actuation energy. Results

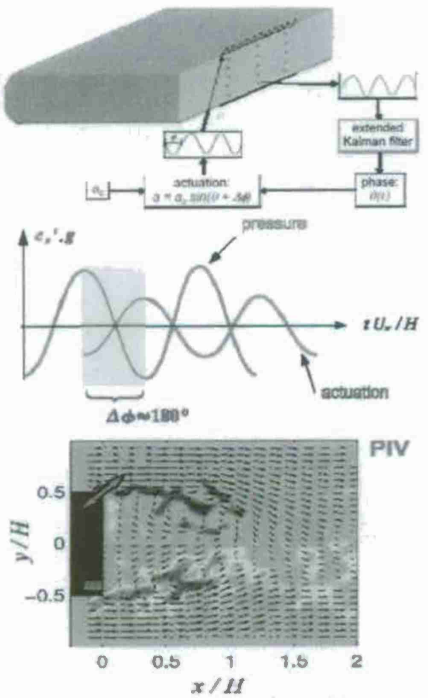

Figure 5. The wake of a 3D bluff body (top), is symmetrized (center) by pulsed actuation at the upper shear layer. Vorticity released at the upper leap is synchronized with preferred lag with sensed pressure at the lower leap (center) using an EKF .

are reported in [J3],[BC2],[P:9,13]. Currently pursued continuation of this project involve the far

Figure 6. A vortex model (left) of a tandem bluff body configuration is used to design a dynamic observer

more challenging tandem configuration, where a multiple vortex model is used a basis for a scented Kalman filter observer (Fig. 6).

<u>3.2 *Feedback control of the lift over a semi-circular wing plan.*</u> The regulation of an LEV and, consequently, the lift, is part of the related MURI project, jointly with Caltech, Princeton U., and IIT, where wind tunnel experiments are held. Collaborating with the Caltech-led team build on cross-feed between simulation studies at Caltech, wind tunnel experiments and reduced order modeling. An effective control mechanism has been identified, using forward pulsed blowing at the leading edge, at an optimized frequency. A simulation study indicates that an effective feedback can be achieved by synchronizing pulsed actuation with a sensor signal, much alike the bluff body control described above. At IIT we investigating viable means to implement feedback, including a detailed modeling effort to enable accurate prediction of actuation variables, including pressure level and the temporal patterns of blowing. In particular, we developed a concept of control base on duty ratio of pulse blowing, as a practical easily implementable framework for feedback flow control [C3,4,8,11-14,17],[P12]. Compared with other applications of duty ratio control, the challenge in feedback design that we currently work on, is due to the nonlinearity of the response to individual pulses.

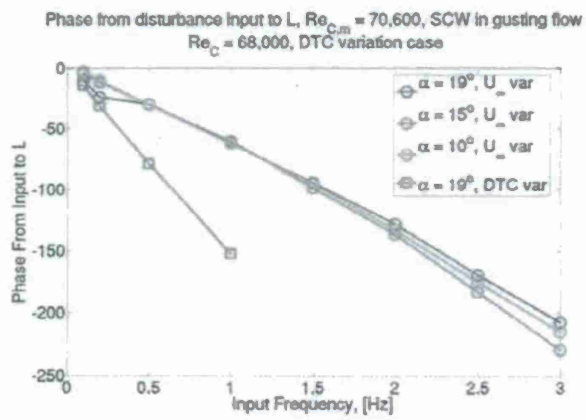

Figure 7. Experimental phase lag in lift response of a semi-circular wingplan to incoming flow velocity variation, and to harmonically modulated duty actuation duty ratio, in open loop.

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Short Course

1. B. R. Noack, G. Tadmor & M. Morzynski (organizers), ***Reduced Order Model for Flow Control***, CISM - International Centre for Mechanical Sciences, Udine, Italy, September 15-19, 2008.

Supported Personnel: Gilead Tadmor, Professor, PI

Interactions/Transitions/Presentations:

i. 1st Int. Active Flow Control Conf., Berlin, September 2006
ii. 45th & 46th AIAA Aerospace Sciences Meetings and Exhibit, Jan. 2007 & 2008
iii. 4th Flow Control / 38th Fluid Dynamics Conference, June 2008
iv. 59th, 60th, Ann. Meetings of the APS DFD, November, 2006 & 2007
v. Workshop on Bluff-Body Wakes, Instabilities and Control[1], Warsaw, 25. & 26. January 2007 (represented by B. R. Noack).
vi. Workshop on Reduced Order Models for Flow & Noise Control, German Armed Forces Univ., Munich, 2/2007 (represented by B. R. Noack).
vii. SIAM Conf. on Math & Comp. Issues in Geosciences, March 2007.
viii. SIAM Conference on Applications of Dynamical Systems, May, 2007.
ix. Seminars at Tel Aviv University (7/2007), U. Maryland (10/2007), George Wash. U. (10/2007), Harvard U. (2/2008)), KTH (Sweden, 5/2008), Weizmann Inst. (Israel, 6/2008.

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14. ABSTRACT
Our focus has been on structural enablers for very low order design models and for model-based flow control, including the flow physics underpinnings of low order flow models. Basic theory investigations concentrated primarily on Galerkin models: We derived from the NSE the essential role and form of mean field models and developed a novel none-equilibrium statistical closure and implied sub-grid turbulence models. Mean-field models now predict lift dynamics and high frequency actuation. With harmonically-pure mode-sets, mode interpolation maintains minimum model order across changing operating conditions, and is assisted by a new, efficient POD computation. Experimental studies were done in conjunction with a related MURI project, and complemented independently supported, long-term international team collaborations. We explored new feedback paradigms, including implementing duty ratio feedback modulation of pulsating jets, validated by MAV lift enhancement, and Lagrangian models in feedback for drag reduction behind a 3D bluff body. The research is presented in 7 journal papers + 2 under review / 1 in preparation, 2 Book chapters, 17 refereed conference papers, 14 conference abstracts, a forthcoming book and an international short course.

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